The littlest Higgs model and Higgs boson associated production with top quark pair at high energy linear e^+e^- collider

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Abstract

In the parameter space allowed by the electroweak precision measurement data, we consider the contributions of the new particles predicted by the littlest Higgs(LH) model to the Higgs boson associated production with top quark pair in the future high energy linear e^+e^- collider(ILC). We find that the contributions mainly come from the new gauge bosons Z_H and B_H. For reasonable values of the free parameters, the absolute value of the relative correction parameter $\delta\sigma/\sigma^{SM}$ can be significanly large, which might be observed in the future ILC experiment with $\sqrt{S} = 800 GeV$.

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I. Introduction

The mechanism of electroweak symmetry breaking($EWSB$) remains the most prominent mystery in current particle physics despite of the success of the standard model(SM) tested by high energy experimental data. The SM accommodates fermion and weak gauge boson masses by including a fundamental Higgs scalar H, which is assumed to responsible to break the electroweak symmetry. However, the SM suffers from problems of triviality, unnaturalness, etc. Thus, the SM can only be an effective field theory below some high energy scales. New physics should exist at energy scales around TeV. Studying $EWSB$ mechanisms other than the simple SM Higgs sector is one of the interesting topics in current particle physics. Little Higgs models[1,2,3] were recently proposed as one kind of models of $EWSB$. The key feature of this kind of models is that the Higgs boson is a pseudo-Goldstone boson of a global symmetry which is spontaneously broken at some higher scale f and thus is naturally light. $EWSB$ is induced by a Coleman-Weinberg potential, which is generated by integrating out the heavy degrees of freedom. This type of models can be regarded as one of the important candidates for the new physics beyond the SM.

The precision electroweak measurement data suggest that the Higgs boson must be relative light and its mass should be roughly in the range of $114.4 GeV \sim 260 GeV$ for $m_t = 178 GeV$ at $95\% C.L.$ [4]. The discovery and study of Higgs boson is one of the most important goals of present and future high energy collider experiments. The LHC will make the first exploration of the TeV energy range, and will be able to discover Higgs boson in the full mass range, provided it exists[5]. After the discovery of the Higgs boson at the LHC, one of the most pressing tasks is a proper determination of the properties of this scalar since it is very important to study the mechanism of $EWSB$ and the generation of mass. The LHC will be able to finish a few measurement on the couplings of the Higgs boson to fermions and gauge bosons but the most precise measurements will be performed in the clean environment of a future high energy linear $e^+ e^-$ collider, the International Linear Collider(ILC)[6].

The top quark, with a mass of the order of the electroweak scale $m_t \approx 178.0 \pm$

$4.36 GeV$[7], is the heaviest particle yet discovered. The coupling of Higgs boson to top quark pair, which is the largest one among the Yukawa couplings, should be detected at high energy experiments. This coupling should play a key role in a theory generating fermion masses and is particularly sensitive to the underlying physics. Thus, studying the $ht\bar{t}$ Yukawa coupling is of particular interest, which is helpful to precision test the SM and search for new physics beyond the SM.

The Higgs boson associated production with top quark pair $t\bar{t}$ at the hadron or lepton colliders plays a very important role both for discovery and for precision measurements of the Yukawa coupling $t\bar{t}h$. Such measurements could help to distinguish the SM Higgs boson from more complex Higgs sectors and shed light on the details of the generation of fermion masses[8]. At hadron colliders, such as LHC, Higgs boson can be associated production with $t\bar{t}$ pair through gg and $q\bar{q}$ sub-process, which has been extensively studied in Ref.[9]. Besides hadron colliders, the ILC can also produce a Higgs boson with $t\bar{t}$ pair via the process $e^+e^- \rightarrow t\bar{t}h$, as long as the Higgs mass is not too large, i.e., $M_h \sim$ $114.4 GeV \sim 260 GeV$[10]. The process $e^+e^- \rightarrow t\bar{t}h$ proceeds mainly through Higgs-boson emission off top quarks, while emission from intermediate Z bosons plays only a minim role. Thus, it is suitable to determinate the coupling $g_{t\bar{t}h}$. If the Higgs boson is light, a precision of around 5% can be reached at an ILC with the c.m. energy $\sqrt{S} = 800 GeV$ and the integrated luminosity $\pounds_{int} \approx 1000 fb^{-1}$[6]. Furthermore, by studying the contributions of the new physics to the process $e^+e^- \rightarrow t\bar{t}h$, one can obtain the bounds on the free parameters of the non-standard models[11]. The purpose of this paper is to calculate the corrections of new particles predicted by the littlest Higgs(LH) model[1] to the process $e^+e^- \rightarrow t\bar{t}h$ and see whether the effects on this process can be observed in the future ILC experiment with $\sqrt{S} = 800 GeV$.

II. $t\bar{t}h$ production cross section in the LH model

The LH model is embedded into a non-linear σ model with the coset space of $SU(5)/SO(5)$. At the scale $\Lambda_s \sim 4\pi f$, the global $SU(5)$ symmetry is broken into its subgroup $SO(5)$ via a VEV of order f, resulting in 14 Goldstone bosons. The effective field theory of these Goldstone boson is parameterized by a non-linear σ model with gauged symmetry

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$[SU(2) \times U(1)]^2$, spontaneously broken down to its diagonal subgroup $SU(2) \times U(1)$, identified as the SM electroweak gauge group. Four of these Goldstone bosons are eaten by the broken gauge generators, leaving 10 states that transform under the SM gauge group as a doublet H and a triplet Φ. This breaking scenario also gives rise to the four new gauge bosons $W_H^\pm$, B_H and Z_H. A new vector-like top quark T is also needed to cancel the divergences from the top quark loop. All of these new particles playing together can successfully cancel off the quadratic divergences of the Higgs boson mass and may produce characteristic signatures at the present and future collider experiments[12,13].
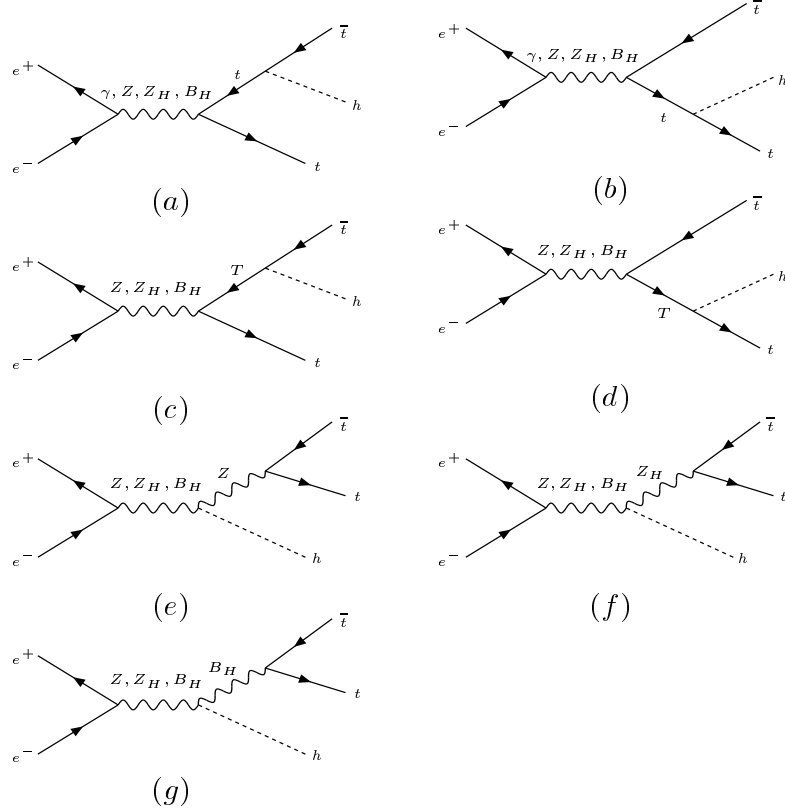

Figure 1: The Feynman diagrams of the process $e^+e^- \to t\bar{t}h$ in the LH model.

The effective non-linear Lagrangian invariant under the local gauge group $[SU(2)_1 \times U(1)_1] \times [SU(2)_2 \times U(1)_2]$, which can be written as [12,14]:

$$\mathcal{L}_{eff} = \mathcal{L}_G + \mathcal{L}_F + \mathcal{L}_Y + \mathcal{L}_\Sigma - V_{CW}, \tag{1}$$

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where $\mathcal{L}_G$ consists of the pure gauge terms, which can give the $3-$ and $4-$particle interactions among the $SU(2)$ gauge bosons. The fermion kinetic term $\mathcal{L}_F$ can give the couplings of the gauge bosons with fermions. The couplings of the scalars H and Φ with fermions can be derived from the Yukawa interaction term $\mathcal{L}_Y$. In the LH model, the global symmetry prevents the appearance of a Higgs potential at tree level. The effective Higgs potential, the Coleman-Weinberg potential V_{CW}, is generated at one-loop and higher orders due to interactions with gauge bosons and fermions, which can induce to $EWSB$ by driving the Higgs mass squared parameter negative. $\mathcal{L}_\Sigma$ consists of the σ model of the LH model.

From the effective non-linear Lagrangian $\mathcal{L}$, one can derive the mass and coupling expressions of the gauge bosons, scalars and the fermions, which have been extensively discussed in Refs.[12,14]. Using these expressions and the relevant SM Feynman rules, we can calculate the production cross section of the process $e^+e^- \to t\bar{t}h$ in the context of the LH model.

The relevant Feynman diagrams for the contributions to the production amplitude of the process $e^+e^- \to t\bar{t}h$ at the order of ν^2/f^2 in the LH model are shown in Fig1.$(a)-$ (g), in which $\nu \approx 246 GeV$ is the electroweak scale. Considering the large masses of the new particles T, Z_H, B_H and the differently Feynman rules, we can surmise that the total contributions of these new particles to this process mainly come from Fig.1(a) and (b). We have confirmed this expectation through explicit calculation. However, to study the total contributions of the LH model to the $t\bar{t}h$ production, we will include all contributions in our numerical calculation. The invariant scattering amplitude of the process $e(p_e) + \bar{e}(p_{\bar{e}}) \to t(p_t) + \bar{t}(p_{\bar{t}}) + h(p_h)$ can be written as:

$$
\begin{aligned}
M \;=\; & \sum_{v_i=\gamma,\ Z,\ Z_H,\ B_H} M_a^{v_i} + \sum_{v_i=\gamma,\ Z,\ Z_H,\ B_H} M_b^{v_i} + \sum_{v_i=Z,\ Z_H,\ B_H} M_c^{v_i T} \\
& + \sum_{v_i=Z,\ Z_H,\ B_H} M_d^{v_i T} + \sum_{v_i=Z,\ Z_H,\ B_H} M_e^{v_i Z} \\
& + \sum_{v_i=Z,\ Z_H,\ B_H} M_f^{v_i Z_H} + \sum_{v_i=Z,\ Z_H,\ B_H} M_g^{v_i B_H}
\end{aligned}
\tag{2}
$$

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with

$$M_a^{v_i} = \overline{u}_t(p_t)\Lambda_{v_i t\bar{t}}^{\mu}\frac{i[(p_{\overline{t}}+p_h)\cdot\gamma+m_t]}{(p_{\overline{t}}+p_h)^2-m_t^2}\Lambda_{ht\bar{t}}v_t(p_{\overline{t}})$$

$$\frac{-ig_{\mu\nu}}{(p_e+p_{\overline{e}})^2-M_{v_i}^2}\overline{v}_e(p_{\overline{e}})\Lambda_{v_i e\bar{e}}^{\nu}u_e(p_e); \tag{3}$$

$$M_b^{v_i} = \overline{u}_t(p_t)\Lambda_{ht\bar{t}}\frac{i[(p_t+p_h)\cdot\gamma+m_t]}{(p_t+p_h)^2-m_t^2}\Lambda_{v_i t\bar{t}}^{\mu}v_t(p_{\overline{t}})$$

$$\frac{-ig_{\mu\nu}}{(p_e+p_{\overline{e}})^2-M_{v_i}^2}\overline{v}_e(p_{\overline{e}})\Lambda_{v_i e\bar{e}}^{\nu}u_e(p_e); \tag{4}$$

$$M_c^{v_i T} = \overline{u}_t(p_t)\Lambda_{v_i t\overline{T}}^{\mu}\frac{i[(p_{\overline{t}}+p_h)\cdot\gamma+M_T]}{(p_{\overline{t}}+p_h)^2-M_T^2}\Lambda_{hT\bar{t}}v_t(p_{\overline{t}})$$

$$\frac{-ig_{\mu\nu}}{(p_e+p_{\overline{e}})^2-M_{v_i}^2}\overline{v}_e(p_{\overline{e}})\Lambda_{v_i e\bar{e}}^{\nu}u_e(p_e); \tag{5}$$

$$M_d^{v_i T} = \overline{u}_t(p_t)\Lambda_{ht\overline{T}}\frac{i[(p_t+p_h)\cdot\gamma+M_T]}{(p_t+p_h)^2-M_T^2}\Lambda_{v_i T\bar{t}}^{\mu}v_t(p_{\overline{t}})$$

$$\frac{-ig_{\mu\nu}}{(p_e+p_{\overline{e}})^2-M_{v_i}^2}\overline{v}_e(p_{\overline{e}})\Lambda_{v_i e\bar{e}}^{\nu}u_e(p_e); \tag{6}$$

$$M_e^{v_i Z} = \overline{u}_t(p_t)\Lambda_{Zt\overline{t}}^{\mu}v_t(p_{\overline{t}})\frac{-ig_{\mu\mu'}}{(p_t+p_{\overline{t}})^2-M_Z^2}\Lambda_{Zv_i h}^{\mu'\nu'}$$

$$\frac{-ig_{\nu\nu'}}{(p_e+p_{\overline{e}})^2-M_{v_i}^2}\overline{v}_e(p_{\overline{e}})\Lambda_{v_i e\bar{e}}^{\nu}u_e(p_e); \tag{7}$$

$$M_f^{v_i Z_H} = \overline{u}_t(p_t)\Lambda_{Z_H t\overline{t}}^{\mu}v_t(p_{\overline{t}})\frac{-ig_{\mu\mu'}}{(p_{\overline{t}}+p_t)^2-M_{Z_H}^2}\Lambda_{Z_H v_i H}^{\mu'\nu'}$$

$$\frac{-ig_{\nu\nu'}}{(p_e+p_{\overline{e}})^2-M_{v_i}^2}\overline{v}_e(p_{\overline{e}})\Lambda_{v_i e\bar{e}}^{\nu}u_e(p_e); \tag{8}$$

$$M_g^{v_i B_H} = \overline{u}_t(p_t)\Lambda_{B_H t\overline{t}}^{\mu}v_t(p_{\overline{t}})\frac{-ig_{\mu\mu'}}{(p_{\overline{t}}+p_t)^2-M_{B_H}^2}\Lambda_{B_H v_i H}^{\mu'\nu'}$$

$$\frac{-ig_{\nu\nu'}}{(p_e+p_{\overline{e}})^2-M_{v_i}^2}\overline{v}_e(p_{\overline{e}})\Lambda_{v_i e\bar{e}}^{\nu}u_e(p_e). \tag{9}$$

Where Λ_{ijk} are the relevant coupling vertices, which have been given in Ref.[12]. The LH model can generate correction terms to the tree-level SM coupling vertices $\Lambda_{Zf\bar{f}}$ and $\Lambda_{ht\bar{t}}$, which can also produce corrections to the process $e^+e^- \to t\bar{t}h$. In our numerical calculation, we will take into account this correction effects.

From above equations, we can see that the $t\bar{t}h$ production cross section σ involves four of the free parameters of the LH model, except the SM input parameters α_e, S_W, M_Z, m_t, and M_h. They are the vacuum condensate scale parameter f, the mixing parameters

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c' and c between the charged and neutral vector bosons, and the mixing parameter $x_L = \lambda_1^2/(\lambda_1^2 + \lambda_2^2)$ between the SM top quark and the heavy vector-like quark T. λ_1 and λ_2 are the Yukawa coupling parameters. At the order of ν^2/f^2, the T quark mass M_T, the B_H mass M_{B_H}, and the Z_H mass M_{Z_H} mainly depend on the free parameters f, x_L; f, c'; and f, c, respectively. The mixing parameters c and c' also control the couplings of the new heavy gauge bosons Z_H and B_H to other particles.

In the LH model, the custodial $SU(2)$ global symmetry is explicitly broken, which can generate large contributions to the electroweak observables. If one assumes that the SM fermions are charged only under $U(1)_1$, then global fits to the electroweak precision data produce rather severe constraints on the parameter space of the LH model[12,14,15]. However, if the SM fermions are charged under $U(1)_1 \times U(1)_2$, the constraints become relaxed. The scale parameter $f = 1 \sim 2TeV$ is allowed for the mixing parameters c, c', and x_L in the ranges of $0 \sim 0.5$, $0.62 \sim 0.73$, and $0.3 \sim 0.6$, respectively[16]. Taking into account the constraints on the free parameters f, c, c' and x_L, we will give our numerical results in the following section.

III Numerical results and summary

To obtain numerical results, we need to specify the relevant SM input parameters. These parameters are $m_t = 178GeV$, $\alpha_e = 1/128.8$, $S_W^2 = 0.2315$, $M_Z = 91.187GeV$[17]. Considering the experimental constraints on the Higgs boson mass M_h[4], we take $M_h = 120GeV$. The c.m. energy $\sqrt{S}$ of the ILC experiment is assumed as $\sqrt{S} = 800GeV$. In our numerical estimations, we will take the parameters f, c, c' and x_L as free parameters.

The relative correction $\delta\sigma/\sigma^{SM}$ is plotted in Fig.2 as a function of the mixing parameter c for $f = 1TeV$ and three values of the mixing parameter c', in which $\delta\sigma = \sigma^{tot} - \sigma^{SM}$ and σ^{SM} is the tree-level production cross section of $t\bar{t}h$ predicted by the SM. We have taken the mixing parameter $x_L = 0.3$, 0.4, 0.5, 0.6 in Fig.2(a), Fig.2(b), Fig.2(c) and Fig.2(d), respectively. From Fig.2 one can see that the total contribution of the new particles predicted by the LH model can enhance or suppress the production cross section of the process $e^+e^- \to t\bar{t}h$, which mainly depends on the values of the mixing parameters c and c' for the fixed of the parameter f. The absolute value of the relative correction

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$\delta\sigma/\sigma^{SM}$ is not sensitive to the mixing parameter x_L, while is sensitive to the mixing parameters c and c'. For $c \geq 0.35$, the value of $\delta\sigma/\sigma^{SM}$ quickly increases as c increasing. This is because, for the fixed parameters c', x_L and f, the correction cross section $\delta\sigma$ is proportional to the factors c^4 and $c^2(c^2 - s^2)$ at the order of ν^2/f^2. The factor $c^2(c^2 - s^2)$ goes to extremum when the mixing parameter c gets close to 0.5. For $c < 0.35$, in most of the parameter space of the LH model, the absolute value of the relative correction $\delta\sigma/\sigma^{SM}$ is smaller than 5%, which is very difficult to be detected in the future ILC experiments. Certainly, it is very easy to observe the correction effects of the LH model on the process $e^+e^- \to t\bar{t}h$ for $c \geq 0.35$.
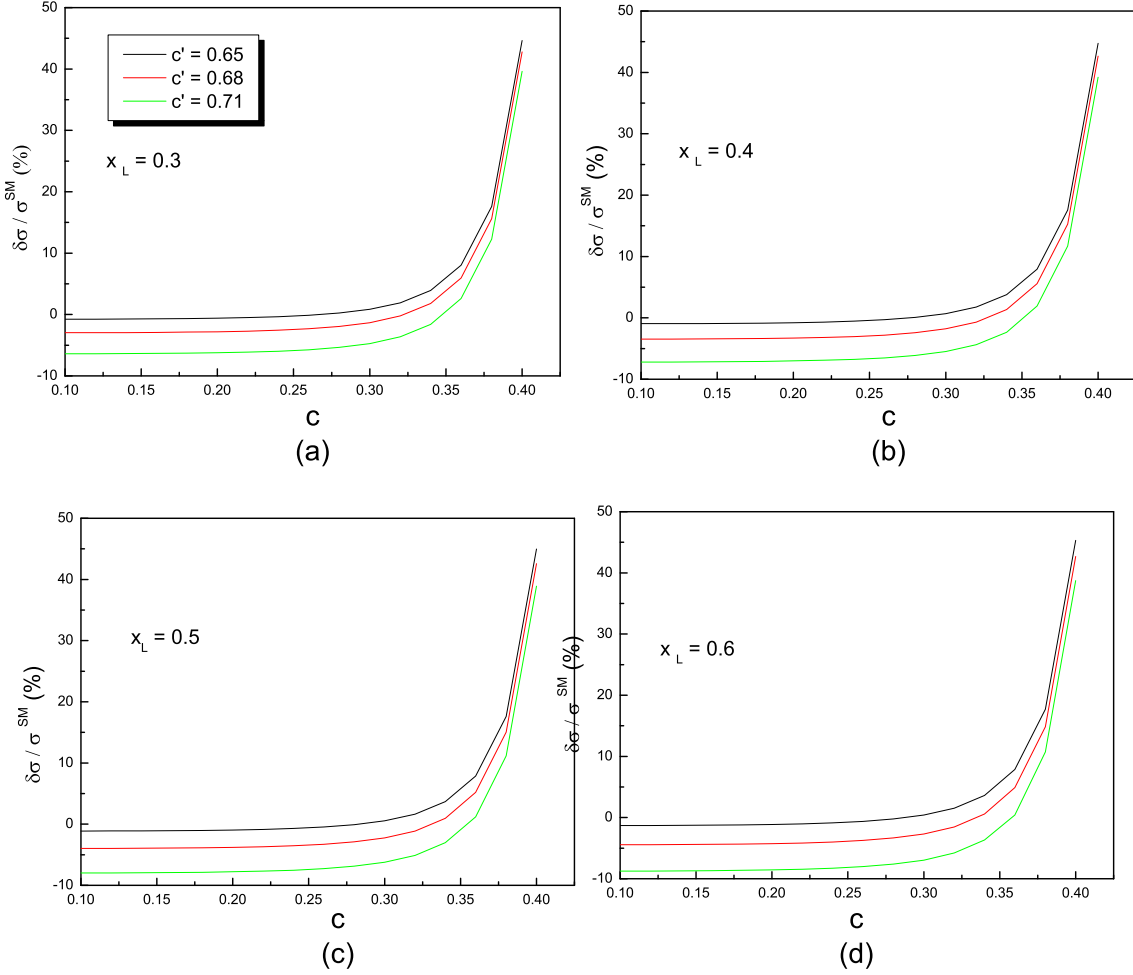

Figure 2: The relative correction $\delta\sigma/\sigma^{SM}$ as a function of the mixing parameter c for $f = 1 TeV$ and different values of the mixing parameters c' and x_L.
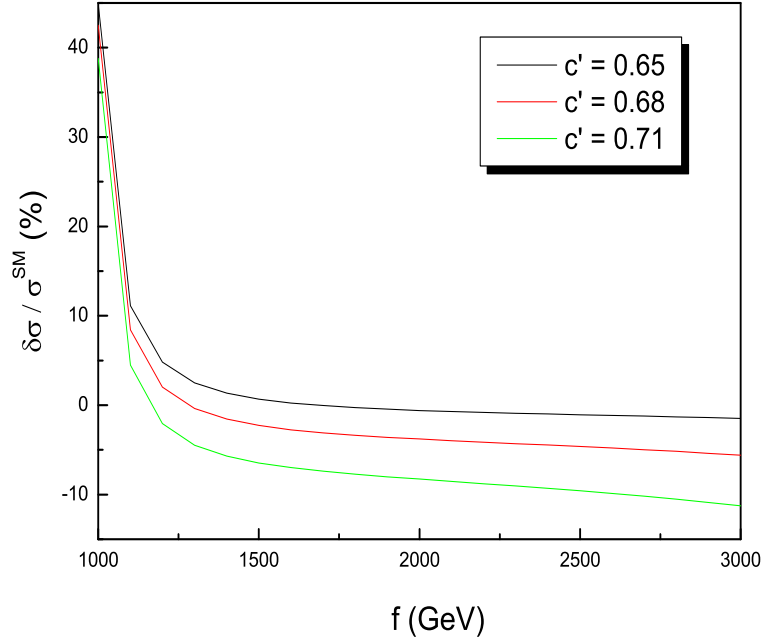
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Figure 3: The relative correction parameter $\delta\sigma/\sigma^{SM}$ as a function of the scale parameter f for $x_L = 0.5$, $c = 0.4$ and three values of the mixing parameter c'.

In general, the contributions of the LH model to observables are dependent on the factor $1/f^2$. To see the effect of varying the scale parameter f on the relative correction $\delta\sigma/\sigma^{SM}$, we plot $\delta\sigma/\sigma^{SM}$ as a function of f for three value of the mixing parameter c' in Fig.3. Taking into account the conclusions obtained from Fig.2, we have taken $x_L = 0.5$ and $c = 0.4$ in Fig.3. One can see from Fig.3 that the total contribution of the LH model to the $t\bar{t}h$ production cross section decreases as the scale parameter f increasing for $f \leq 1.2TeV$ with $c' = 0.68$. However, for $1.2TeV < f \leq 4.8TeV$, the value of $\delta\sigma/\sigma^{SM}$ is negative and its absolute value increases as f increasing. This is because the contributions of the LH model to the $t\bar{t}h$ production cross section mainly come from Z_H exchange and B_H exchange. Z_H exchange has positive contributions which quickly decrease as the scalar parameter f increasing, while B_H exchange has negative contributions which slowly decrease as f increasing. For $f > 5TeV$, the total contributions to the $t\bar{t}h$ production

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cross section get close to zero. Thus, in general, the total contributions decouple for large of the scale parameter f, which is similar to the contributions of the Lh model to for other observables.

The LH model[1] is one of the simplest of the little Higgs models, which predicts the existence of the four new heavy gauge bosons Z_H, B_H, and $W_H^{\pm}$, a vector-like top quark and a triplet of heavy scalars except the SM particles. Some of these new particles can generate significant corrections to the electroweak precision observables and thus the precision measurement data can give severe constraints on the parameter space of this type of models. In the parameter space of the LH model($f = 1 \sim 2TeV$, $c = 0 \sim$ 0.5, $c' = 0.62 \sim 0.73$) preferred by the electroweak precision data, we study the process $e^+e^- \to t\bar{t}h$. We find that the contributions of the LH model to this process mainly come from Fig.1(a) and (b) generated by Z_H exchange and B_H exchange, which can enhance or suppress the $t\bar{t}h$ production cross section σ^{SM} predicted by the SM at the tree-level. In sizable regions of the parameter space, the absolute value of the relative correction $\delta\sigma/\sigma^{SM}$ is larger than 5%, which might be detected in the future ILC experiments.

Certainly, the modification to the relation between the SM free parameters can also produce contributions to the processes $e^+e^- \to t\bar{t}h$. However, our calculation results show that the contributions are smaller than those of Z_H exchange and B_H exchange at least by one order of magnitude in wide range of the parameter space of the LH model. Thus, comparing with the direct contributions of Z_H and B_H, the contributions from the modification to the relation between the SM free parameters can be safely neglected.

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